THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

The low-carbon steel industry

- Interactions between the hydrogen direct reduction of steel and the electricity system

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

The European steel industry must achieve deep reductions in CO_2 emissions to meet the targets set out in the Paris Agreement. Options for reducing CO_2 emissions include electrification, carbon capture and storage (CCS) and the use of biomass. The rapid decline in the cost of renewable electricity makes expanded electrification an attractive option for eliminating the dependence of the steel industry on coal. This work investigates how electrification of the steel industry via the use of a hydrogen direct reduction steel-making process can interact with the electricity system towards achieving zero CO_2 emissions from both the steel industry and electricity sector.

In this work, the concept of techno-economic pathways is used to investigate the potential implementation of CO_2 abatement measures over time towards zero-emissions steel production in Sweden. Two different techno-economic optimisation models are used. The first model is used to investigate the impacts of electricity price variations on investments and the operation of steel production. The second model is applied to study the interaction between an electrified steel industry and the future electricity system of northern Europe.

The results show that in Sweden, it will be feasible to reach close-to-zero CO_2 emissions from steel production by Year 2045 with electrification via a hydrogen direct reduction process. We also show that increased production of hot briquetted iron (HBI) pellets could lead to the decarbonisation of the steel industry outside Sweden, assuming that the exported HBI will be converted via electric arc furnace (EAF) and that the receiving country has a decarbonised electricity generation system.

The results also indicate that the cost-optimal design of the steel-making process is strongly dependent upon the electricity system composition. It is found to be cost-efficient to invest in overcapacity in steel production units (electrolyser, direct reduction shaft (DR shaft) furnace and EAF) and in storage units for hydrogen and HBI, to allow operation of the steel production capacity to follow the variations in electricity price.

The modelling shows that an electrified steel industry could increase the electricity demand of northern Europe by 11% (by 183 TWh), and that the spatial allocation of the electrified steel production capacity could differ from the current allocation of steel plants. It is found that certain factors, such as the availability of low-cost electricity generation and access to iron ore, significantly influence the allocation of electrified steel plants. The modelling results show that the additional electricity demand from an electrified steel industry is met mainly by increasing outputs from wind and solar power, whereas natural gas-based electricity production is reduced, as compared to an electricity system in Year 2050 without an electrified steel industry.

Keywords: electrification, electricity system modeling, steel industry, hydrogen-direct reduction, storage, flexibility

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. A. Toktarova, I. Karlsson, J. Rootzén, L. Göransson, M. Odenberger and F. Johnsson (2020). "Pathways for low-carbon transition of the steel industry—a Swedish case study". *Energies*, 13(15), 3840. DOI: 10.3390/en13153840

II. A. Toktarova, L. Göransson and F. Johnsson (to be submitted). "Impacts of electricity price variations on investments in steel production capacities applying a hydrogen direct reduction process".

III. A. Toktarova, V. Walter, L. Göransson and F. Johnsson (to be submitted). "Electrified steel production - A northern European energy system study".

Alla Toktarova is the principal author of **Papers I – III** and performed the modelling and analysis for all three papers. Professor Filip Johnsson contributed with discussion and editing to **Papers I-III**. Lisa Göransson contributed to the method development in **Papers II** and **III**, as well as with editing and discussion for all three papers. Ida Karlsson, Johan Rootzén and Mikael Odenberger contributed with reviewing and discussion of **Paper I**. Viktor Walter contributed with modelling and discussion of **Paper III**.

Other publications by the author, not included in the thesis:

A. A. Toktarova, I. Karlsson, J. Rootzén and M. Odenberger (2020). "Mistra Carbon Exit Technical roadmap - Steel industry". [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-steel-industry

B. I. Karlsson, A. Toktarova, J. Rootzén and M. Odenberger (2020). "Mistra Carbon Exit Technical Roadmap - Cement Industry". [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-cement-industry.

C. I. Karlsson, A. Toktarova, J. Rootzén and M. Odenberger (2020). "Mistra Carbon Exit Technical Roadmap - Buildings and Transport Infrastructure". [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-buildings-and-transportinfrastructure.

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Toktarova Alla,
Göteborg, May 2021

Table of Contents

1. Introduction

In 2019, the European Commission (EC) launched the European Green Deal [1], which aims to make Europe the first climate-neutral continent by Year 2050. To achieve complete decarbonisation by Year 2050, the Green Deal states that the EU should decarbonise its industry, which currently accounts for 20% of the EU's greenhouse gas emissions. In March 2020, the EC presented a New Industrial Strategy for Europe [2], at the primary goal of which is to manage the transition of industry towards climate neutrality and digital leadership.The steel industry is one of the most carbon-emitting and energy-consuming sectors in Europe. The production of steel relies heavily on coal as an input to the traditional blast-furnace-based steel production process that produces primary steel from iron ore. Almost 60% of all steel in the EU is produced via the blast-furnace-based production route [3]. Today, the steel industry accounts for approximately 4% of CO_2 emissions in the EU [4]. Unlike the electricity sector, the steel industry has relatively few technical options to achieve deep cuts in emissions. Significant reductions of CO_2 emissions from primary steel production can be achieved by either electrification measures, such as hydrogen direct reduction (H-DR), hydrogen plasma smelting and electrolysis of iron ore) or using a blast furnace with CCS in combination with biomass. The rapid decline in the cost of renewable energy technologies that has occurred over the last decade [5] has made steel production that incorporates hydrogen produced by electrolysis a potentially attractive option to reduce CO_2 emissions from steel production. A hydrogen-based direct reduction technology is currently being tested in the Swedish HYBRIT project with the aim of introducing fossil-free steel to the market in 2026 [6]. Since the cost of electricity is assumed to be a substantial part of the cost of the H-DR steel-making process, the configuration of the electricity system should have a significant impact on the operation of the steel plant. In the electricity system, in which wind and solar power are expected to dominate the electricity generation mix, significant variations in electricity prices are expected, with more time periods of low and high electricity prices and fewer time periods of moderate electricity prices, as compared with an electricity system dominated by thermal generation [7]. As for the H-DR steel-making process, it allows flexible production of steel through the storage of hot-briquetted iron (HBI) pellets and electricity demand adaptability through flexible operation of steel production capacity and hydrogen storage. Electricity price variations, caused by the weather-dependent generation of solar PV and wind power, and the cost structure of the H-DR steel-making process both affect the cost-efficient sizing of steel production units, which in turn influence the cost of electricity for steel production. Comprehensive electrification of steel production will create an additional electric load and necessitate efficient integration of steel production into the electricity system. According to the EUROFER Low Carbon Roadmap [8], the transition of the European steel industry to low- or zero-carbon emissions will require 400 TWh of CO_2-free electricity in Year 2050. This corresponds to more than seven-times the current purchases of electricity by the steel industry from the grid, and around 13% of Europe’s (EU27) current electricity production. Steel electrification will, therefore, strongly influence the investments in electricity generation capacity and the storage options available, as well as the operation of the dispatchable part of the electricity generation system. The steel industry has in the past undergone revolutionary technological changes, such as the transition from the open hearth to basic oxygen furnace or from bulk casting to continuous casting [9], [10]. These changes were prompted by significant gains in efficiency and product quality. A transition to steel production via the H-DR process is mainly motivated by climate policy considerations.

1.1 Aims and scope

The overall goal is to analyse how electrification of the steel industry interacts with (influences and is influenced by) the electricity system when attaining zero CO_2 emissions from both the steel industry and electricity sector. This thesis focuses on the electrification of primary steel production via H-DR, whereby the hydrogen is produced from renewables. The specific objectives of this thesis aims are to:

I. Analyse the development of the iron and steel industry towards becoming carbon-neutral, taking into account the dynamics of the transition, i.e., proposing decarbonisation pathways that consider which technology options are available and when it is reasonable to assume that these can be implemented.

II. Identify the implications of a future with volatile electricity prices for the cost of steel production via the H-DR process.

III. Investigate the interactions between the electrified steel industry and the electricity system, in particular, the electricity system impact on the spatial allocation and size of new steel plants and the impact of an electrified steel industry on investment decisions related to new electricity generation capacity.

These three objectives form the basis for **Papers I–III**, appended to this introductory essay. The Swedish iron and steel industry is used as a case study in **Paper I**. In **Papers II** and **III**, techno-economic optimisation models are developed and used. **Paper II** focuses on the impacts of the electricity system on electrified steel production. In **Paper II**, parameters such as the electricity prices in southern Germany and northern UK are given as inputs to the model, to capture the different conditions for generation from wind and solar power. **Paper III** describes a case study for the steel industry and electricity system of northern Europe.

1.2 Contributions of the thesis

The thesis consists of this introductory essay and three appended papers. The techno-economic pathways concept used in **Paper I** analyses the extent to which CO_2 abatement measures in the steel industry can reduce emissions if combined to maximise their potentials based on an implementation time-line that is linked to their technical maturity and to the age structure of the existing capital stock.

In **Paper II**, a model is developed to study how electricity price variations affect the steel production capacities that apply to the H-DR steel-making process in terms of: (i) investments; and (ii) the operational times and operational levels of the steel production capacities, including storage utilisation.

In **Paper III**, an existing electricity system model is utilised and complemented with equations, variables and parameters to represent the electricity demand from electrified steel production. The paper describes how electrified steel production can influence: (i) the spatial allocation of new steel plants and their sizing; (ii) the investment decisions related to new electricity generation capacity; and (iii) the commodity trade flows between the regions investigated.

2. Background

This chapter gives a short introduction to the concepts that are in focus in this thesis.

Steel-making in Europe today

In 2019, the total steel production in the EU corresponded to 16% of the global steel output [11]. In Europe, two conventional steel production technologies are currently applied: an ore-based steel-making process using blast furnaces/basic oxygen furnaces (BF/BOF); and a scrap metal-based steel production process that employs electric arc furnaces (EAF) [3]. Within the BF/BOF process, iron ore is reduced to pig iron using reducing agents in a blast furnace. In a basic oxygen furnace (BOF), pig iron together with ferrous scrap is processed and transformed into crude steel. Almost 60% of all EU steel is produced via the BF/BOF production route. Overall, 26% of the iron ore supply for the European steel industry comes from domestic production, and the remainder is from imports [11]. Sweden accounts for almost 80% of all iron ore produced in the EU [12]. EAF requires ferrous scrap and electricity as major inputs. Oxygen and natural gas are used to generate complementary chemical heat for the melting process. Secondary steel-making with EAF results in the production of steel of lower quality compared to virgin steel, since scrap steel retains contaminants, such as copper. Energy and raw materials combined account for 60%–80% of steel production costs [13].

Hydrogen direct reduction

Figure 1 shows a schematic of the hydrogen-based direct reduction process. It consists of hydrogen production in an electrolyser, HBI production in a DR shaft furnace, and steel production in an EAF. Hydrogen and HBI can be stored. The electrolyser, DR shaft furnace and EAF are in this work referred to as the *steel production capacity*.

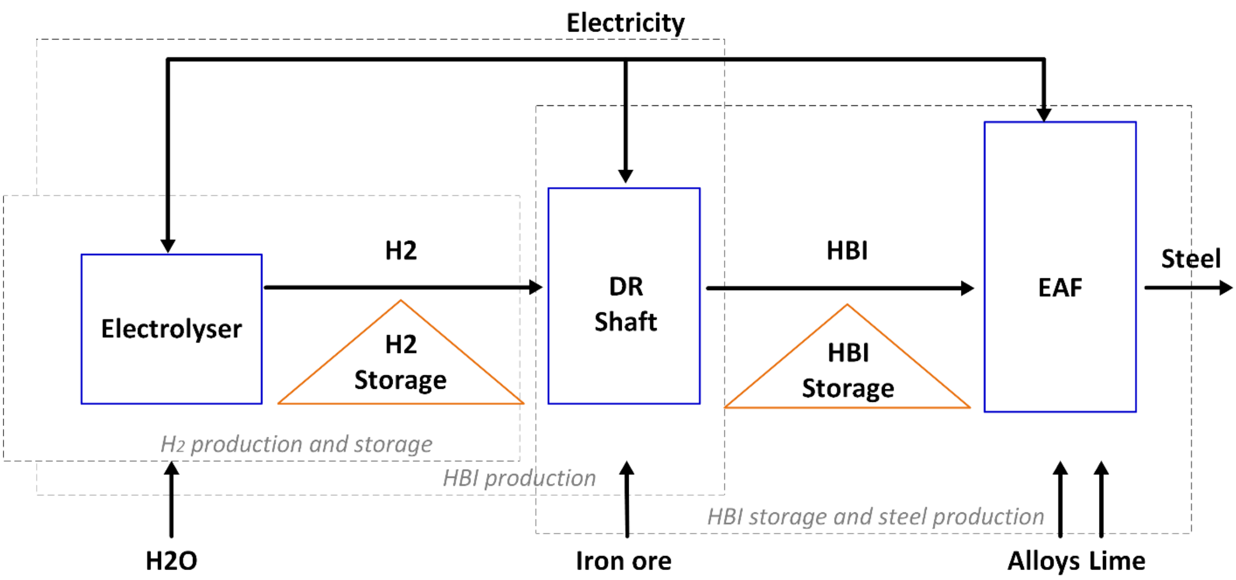

Figure 1. Schematic representation of the hydrogen direct reduction (H-DR) process.

In this work, we assume that what is commonly referred to as ‘green hydrogen’, i.e., hydrogen generated by electrolysis using low-carbon electricity sources such as renewables [14], is used in the H-DR process. Electrolysis is the process in which electricity is used to split water into hydrogen and oxygen. During the iron production step, the iron ore pellets are reduced to direct reduced iron (DRI) by adding hydrogen as the reducing agent in a shaft furnace. To avoid re-oxidisation, the DRI is compacted into HBI, thereby enabling the DRI to be stored and transported without the need for special precautions [15]. In the steel production step, HBI is further converted to liquid steel in an EAF. The electrolyser and EAF have high levels of operational flexibility, i.e., these units can be stopped and started relatively quickly and at a low cost. The electrolyser has a low minimum load, short start-up time and a high ramping rate [16]. The EAF is flexible in terms of changing the power consumption rate [17] and it can be stopped and started in response to the prevailing level of demand [18]. The direct reduction shaft furnace can be operated in a flexible manner between the minimum load level and rated capacity without any decrease in efficiency [19]. The temporal distribution of the electricity consumption of the process can be made flexible through the operational flexibility of the steel production capacity, i.e., the electrolyser, the DR shaft furnace and the EAF, as well as through the storage of hydrogen and HBI.

2.1 Related research

Electrification of steel production is expected to play a key role in the low-carbon transformation of the European steel industry [20]. Table 1 gives an overview of the hydrogen demand from the steel industry in Year 2050, as obtained from the European climate policy and industrial scenarios and the European steel industry roadmap. The electricity demand will increase significantly as a result of conversion of the European steel industry to steel production using hydrogen.

Table 1. Potential hydrogen demand from the steel industry in Year 2050.

Publication type	**Assumptions**			**Hydrogen consumption, Europe in Year 2050, TWh**	**Reference**
	Year	*Production volume, Mtonne*	*Steel production technology*		
Industrial scenario	2050	11 11	H-DR/EAF Plasma steel (H_2)	100	[21]
Climate-policy scenario	2050	35 (20% of the current European steel production)	H-DR/EAF	140	[22]
Sector-specific roadmap	2050	100	H-DR/EAF	234	[8]

Several studies published in recent years have dealt with the techno-economic aspects of the H-DR process [23]–[26]. Arens et al. [24] analysed four future pathways to a low-carbon steel production industry in Germany up to Year 2035 by estimating technical options, specific energy consumption, and CO_2 emissions from the German steel industry. They concluded that, in order to reduce CO_2 emissions from steel production to close to zero, alternative steel-making processes (H-DR, steel electrolysis) need to be developed, while CO_2 reduction measures in the short term (through heat recovery, scrap usage and the use of by-products to produce base chemicals) also need to be realized. Fischedick et al.[25] have presented techno-economic models that can be used to compare to the reference blast furnace route three innovative ore-based steel-making routes: a blast furnace with CCS (BF-CCS); H-DR; and iron ore electrolysis (EW). They have shown that H-DR is, in both economic and environmental respects, the most attractive route to produce steel, since decoupling hydrogen production from continuous operation of the steel plant through hydrogen storage provides the opportunity to use low-cost renewable electricity. Vogl et al. [26] have assessed the energy use, CO_2 emission mitigation potential, and economic performance of the H-DR steel-making process, and have shown that the variability of electricity prices is important to consider in the context of dimensioning steel production capacities and storage sizes.

Only a few studies have investigated a hydrogen-based steel industry from the electricity systems perspective. Göransson and Johnsson [27] investigated the possibility to use hydrogen production to allow the steel industry to manage variable generation in the electricity system. In that study, an electricity system dispatch model was applied, and a complete shift from using coal to using hydrogen as the reducing agent in all the integrated steel plants in Europe was assumed. The results of the modelling showed that the H-DR process reduces the average cost of electricity generation and increases profits for the wind power owner as the wind shares increase. Göransson et al. [7] analysed the impact of electrification of the steel industry, passenger vehicles, and the residential heat supply on the northern European electricity system using a semi-heuristic, cost-minimising investment model. They demonstrated that a strategic, flexible demand for electricity in different sectors enables a faster transition from fossil fuels in the European electricity system and reduces the overall system costs, as compared to electrification without provision for flexibility, given the assumptions made in the modelling. With respect to steel production, that study assumed electrification with a continuous demand for hydrogen at the same locations as steel is produced today. Johansson and Göransson [28] studied the impacts of electrified steel production with hydrogen storage on the cost-optimal electricity system composition. In their paper, electrified steel production is presented as the hourly hydrogen demand evenly distributed over 1 year and investments in hydrogen storage are allowed. A regional green-field investment model was used. They found that in regions with good conditions for variable renewable electricity generation, electrified steel production with hydrogen decreases the total installed capacity by reducing curtailment and investments in biogas turbine capacity, as compared to the case without electrified steel production and without hydrogen storage.

Although the above studies show that steel production electrification has the potentials to provide CO_2 emissions reductions and stimulate the expansion of low-carbon electricity generation technologies, there is still a lack of knowledge regarding how an electrified steel sector would influence future investments in steel plants and electricity generation in different regions. This study aims to bridge this gap in the knowledge regarding the interaction between an electrified steel industry and an electricity system with a large share of non-dispatchable electricity generation.

3. Method

In this work, three methods have been utilised, as applied in **Papers I** to **III**. This section provides an overview of the models, assumptions and input data used in the three appended papers. In Figure 2, the three models with their main inputs and outputs are presented. In **Paper I**, the concept of techno-economic pathways is used to investigate the potential implementation of CO_2 abatement measures over time towards zero-emissions steel-making. For **Paper II**, a Steel Process (SP) model was developed to investigate the impacts of the electricity price variations on steel production capacities applying the H-DR process, as described in Chapter 3.2. In **Paper III**, an existing linear electricity system optimisation model, ENODE, is further developed and applied to study the interactions between an electrified steel industry and the electricity system. The ENODE model minimises the cost of investments and operation to meet the electricity demand and – in the developed version of this work – it provides the demand for steel and, thereby, an understanding of the interactions between the electricity system and the electrified steel industry. The temporal scope of **Papers II** and **III** is Year 2050, modelled with one-hour time resolution in **Paper II** and with a 12-hour time resolution in **Paper III** (each time-step represents the average of 12 hours).

As indicated by the arrows on the left-hand side of Figure 2, several of the models use the same or similar input data. The economic data for investments and operational costs of steel production technologies, as well as the raw material consumption levels and associated costs are used in **Papers I–III**. The average technical lifetime of steel-making technologies and technology readiness levels of CO_2 abatement measures are used to design a development time-line for the pathways in **Paper I**. The selection and combination of the CO_2 abatement measures in **Paper I** are made in line with governmental climate goals and the visions of the steel companies, as well as being based on a comprehensive literature review. Assumptions as to steel demand are utilised as an input in **Papers II–III**. Hourly electricity price profiles representing two regions with different conditions for renewable electricity (southern Germany and northern UK) are inputs in **Paper II**. Investment costs and fixed/variable O&M costs for electricity generation technologies and hourly generation profiles for solar and wind power are considered in **Paper III**. In **Papers I–III**, the sum of the capital and variable operating costs, where the variable operating cost includes the cost of electricity, the cost of raw materials, and other costs associated with running the steel process, is determined as the total steel production cost. The outputs of the methods are detailed in Chapter 4.

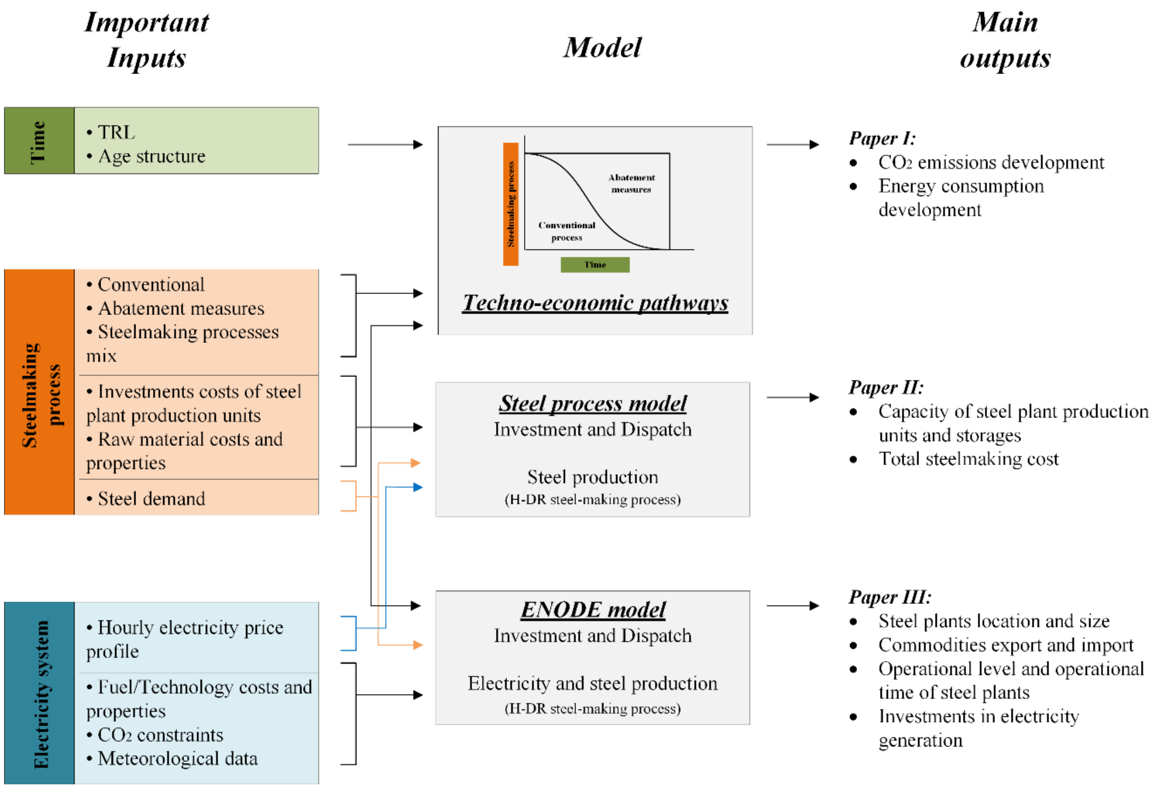

Figure 2. Overview of the models used in this work and their main input and outputs.

Table 2 provides a summary of the investigated subjects, time and geographical scopes, sectors and steel-making technologies applied in the appended **Papers I–III**.

Table 2. Summary of the studies described in the appended papers, including the modelling dimensions.

	Paper I	**Paper II**	**Paper III**
Under investigation	Transition to low carbon steel production	Impact of electricity system on the steel production	Interactions between the electrified steel industry and the electricity system configuration, assuming net-zero emissions from both sectors
Time period	Yearly, from 2020 to 2045	Hourly for Year 2050	Twelve-hourly for Year 2050
Geographical regions	Sweden	Southern Germany and northern UK	Northern Europe
Sectors	Steel industry	Steel industry	Electricity system and steel sector
Steelmaking technologies	BF/BOF, EAF, TGRBF/BOF + CCS + Biomass, H-DR/EAF	H-DR/EAF	H-DR/EAF

3.1 Techno-Economic Pathways (Paper I)

The techno-economic pathways are defined as a series of technological and economic investments that connect current steel industry configurations to a desirable low-carbon future [29]. Through technological characteristics, the pathways reveal sectoral-level changes. The pathway analysis involves the following steps:

1. Define inputs for the techno-economic modelling in terms of costs, CO_2 reduction potential, and specific energy inputs of CO_2 abatement measures;
2. Ensure that the selection and combination of CO_2 abatement measures is in line with governmental climate goals, as well as the literature;
3. Design a pathways time-line that is based on the pace of decommissioning the conventional steel-making technologies and that considers the assumed development of the technology readiness levels of the CO_2 abatement measures included; and
4. Based on the technology readiness level time-line, estimate a time-line for investments in abatement measures to replace current processes, prompting a shift in innovative technology diffusion patterns.

The techno-economic pathways are applied to estimate the evolution of the levels of CO_2 emissions and energy consumption over time, as well as the cost of steel production.

3.2 Steel process model (Paper II)

The Steel Process (SP) model was developed for this work to study the impacts of electricity price variations on steel production capacities that apply the H-DR process. The overall objective of the SP model, which is a linear optimisation model, is to design the operational times and operational levels of the steel production capacities, as well as the utilisation of storage units, such that the steel demand is satisfied at the lowest total steel production cost C^{tot}, i.e., the sum of the costs of investment C_p^{inv}, operation $C_{p,t}^{run}$, and cycling $C_{p,t}^{cycl}$. The total steel production cost, which should be minimised, can therefore be written as:

$$minC^{tot} = \sum_{p \in P} C_p^{inv} i_p + \sum_{p \in P} \sum_{t \in T} (C_{p,t}^{run} g_{p,t} + C_{p,t}^{cycl}) \tag{1}$$

where *P* is the set of steel production capacities (electrolyser, DR shaft furnace and EAF) and storage technologies (hydrogen and HBI storage units), and *T* is the set of time-steps.

Electricity price profiles

A main goal of **Paper II** is to investigate how electricity price variations influence the steel production capacities in the H-DR steel-making process. Both actual and modelled electricity prices are deployed in the analysis. The electricity price profiles representing the current (Year 2018) electricity prices in Germany and the UK are obtained from Epexspot [30] and NordPool [31], respectively. The electricity price profiles for Year 2050 are derived from the electricity system investment model H2D [7]. Figure 3 presents the average electricity price, together with a volatility index for the electricity price profiles. The volatility index is introduced and calculated according to the method applied by Beiron [32]. The volatility index, I_v, of the electricity price profile is defined as:

$$I_v = \frac{\int_{t_1}^{t_2} (p_t - p^{average})^2 dt}{100(t_2 - t_1)} \tag{2}$$

. where p_t is the electricity price at time *t*, and $p^{average}$ is the average electricity price.

The volatility index indicates an increase in the number and duration of both the high- and low-price electricity periods due to high shares of renewables in the two countries in Year 2050, as compared with the Year 2018 electricity price profiles. For the electricity system in the northern

UK, the extensive low-electricity price periods in Year 2050 result in an average electricity price that is 20% lower than that of southern Germany during the same time period.

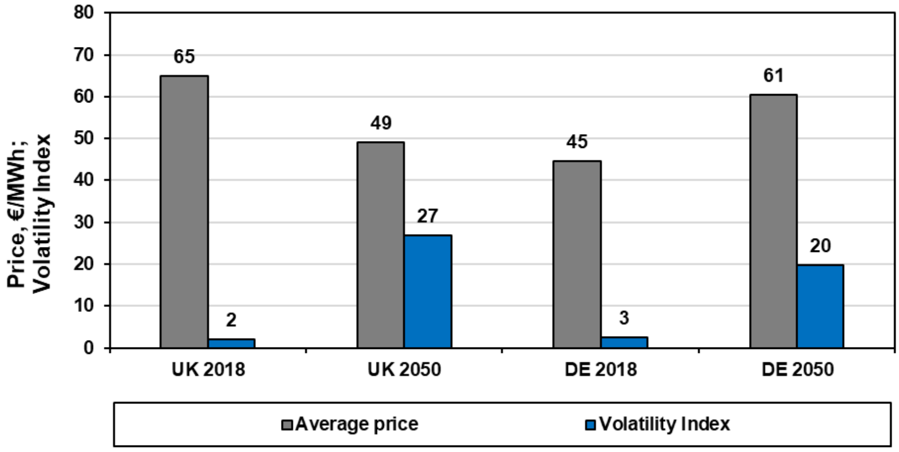

Figure 3. Average electricity prices and electricity price volatility indices for Germany and the UK in Year 2018, and for southern Germany and northern UK in Year 2050.

3.3 ENODE (Paper III)

To study the interaction between the electrified steel production and electricity system, the ENODE model was refined by adding the SP module. The ENODE model was first presented by [33] and was further developed subsequently [28]. The ENODE version used in this work minimises the costs for investments in and operation of the electricity system and steel industry, while meeting the demands for electricity and steel. The ENODE model is a green-field model, in which a new system is designed from scratch.

The objective function ENODE model is expressed as:

$$\begin{aligned} minC^{tot} = \sum_{r \in R} ((& \sum_{p \in P \setminus P^{transm}} (i_{p,r}(C_{p,r}^{inv} + C_{p,r}^{O\&M,fix}) + \sum_{t \in T} (C_{p,t,r}^{cycl} + C_{p,t,r}^{run} g_{p,t,r})) \\ & + \sum_{r_2 \in R \setminus r} (\sum_{p \in P^{transm}} C_{p,r,r_2}^{inv} \, i_{p,r,r_2} \\ & + \sum_{p \in P^{steel} \cup P^{transm}} \sum_{t \in T} C_{r,r_2}^{transp} (e_{p,t,r,r_2}^{pos} + b_{t,r,r_2})) \end{aligned} \tag{3}$$

where P is the set of technologies, including the electricity generation technology, steel production technology, electricity and steel storage units, and transmission lines, R is the set of regions and T is the set of time-steps. The total system costs, C^{tot}, consider the investment costs and the fixed and maintenance costs, $C_{p,r}^{inv}$ and $C_{p,r}^{O\&M,fix}$, respectively, per unit of capacity, $i_{p,r}$. The variable operation running cost, $C_{p,t,r}^{run}$, is calculated for electricity generated and commodity produced $g_{p,t,r}$. The cycling costs of thermal power plants and DR shaft furnaces, $C_{p,t,r}^{cycl}$, depend on the frequencies of start-ups and part-load operation. The transportation cost and small transmission cost, C_{r,r_2}^{transp}, are considered between regions for electricity and commodity trading, e_{p,t,r,r_2}^{pos}, as well as for iron ore trading, b_{t,r,r_2}.

4. Selected results and discussion

This chapter describes the main findings from the appended **Papers I–III** in relation to the overall aim of this work. The chapter deals with: 1) the techno-economic pathways for the steel industry in terms of the development of energy consumption and CO_2 emissions over time; 2) the impact of the electricity price variations on steel production applying the H-DR process; and 3) the interactions between the electricity system and the electrified steel industry.

4.1 The techno-economic pathways towards zero-emissions steel-making in Sweden

Figure 4 visualises the three production pathways for the Swedish steel industry, showing: (i) the timing of replacement of current technologies (a–c); and (ii) the energy consumption levels (d–f) for both primary and secondary steel-making technologies.

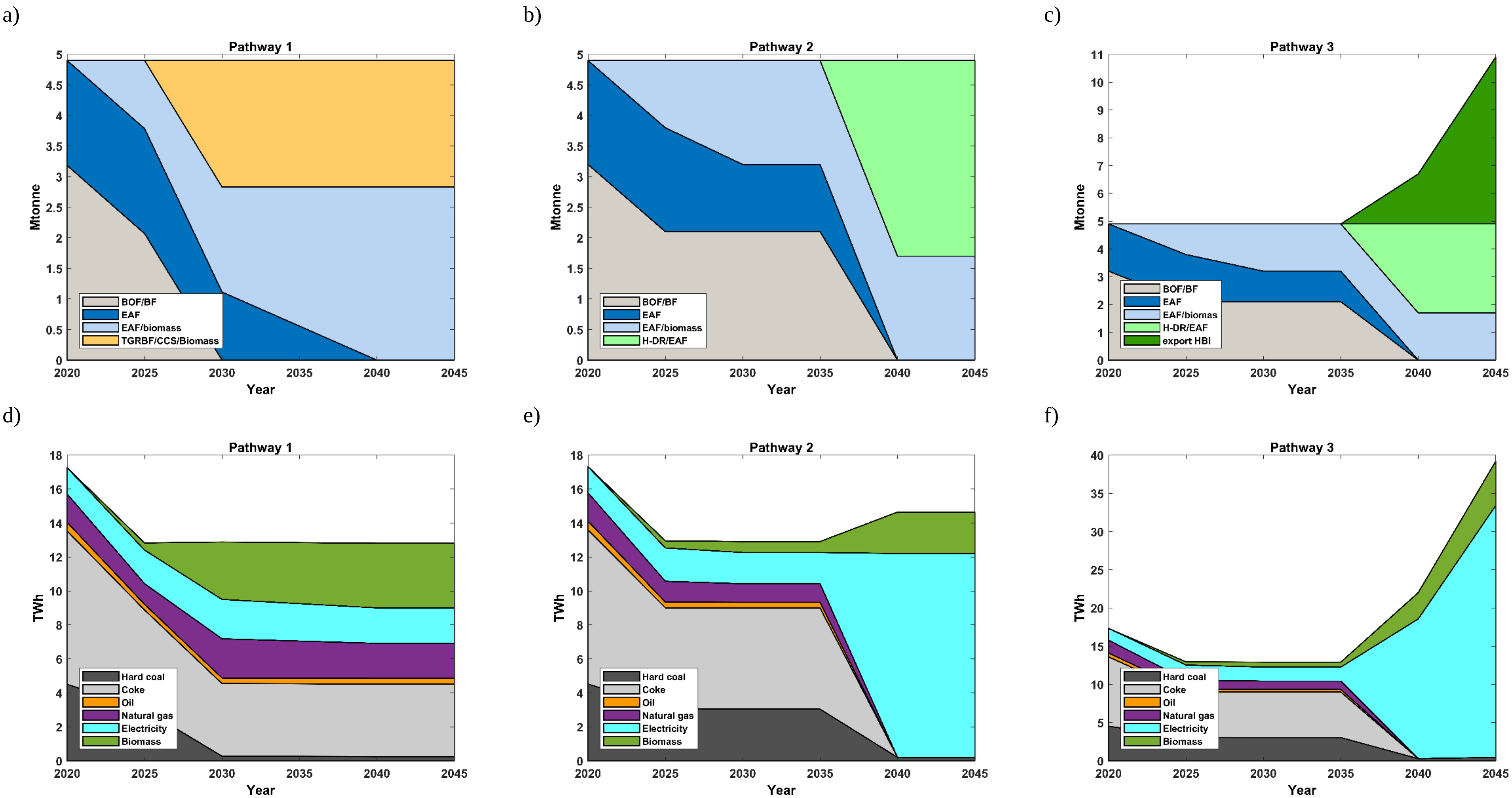

Figure 4. Summary of the results from the case study in Paper I. Production processes mix (a–c) and energy use (d–f) for the Swedish steel industry pathways from Year 2020 to Year 2045. Note the different scales of the *y*-axis in panels c and f. [*Source: Figures 2 and 3 in Paper I*]

Production processes mix. Pathway 1 (Figure 4a) represents shifts towards using the top gas recycling blast furnace (TGRBF) with carbon capture and biomass for conventional primary steel production and towards using the EAF with biomass for secondary steel production. From Year 2025, the production level of iron-ore based steel will be equivalent to 42% of the total steel production in Sweden (4.9 Mtonne) owing to the retirement of one blast furnace [34]. By Year 2030, the primary steel production technology is replaced by a combination of TGRBF and CCS technologies and coal for pulverised coal injection (PCI) is replaced with biomass. As regards the CO_2 capture technology, a post-combustion technology is assumed. In Pathways 2 and 3 (Figure 4, b and c), conventional primary steel-making is replaced by the H-DR steel-making process, which is assumed to be implemented by Year 2040 [34]. Between 2025 and 2040, steel is produced in the EAF with biomass at a level corresponding to about 58% of the current total production, which is due to the retirement of one blast furnace in Year 2025. From Year 2040, for Pathways 2 and 3, the shares of primary and secondary steel-making are assumed to be at the current levels (Figure 4, b and c). For Pathway 3 (Figure 4c), the export of iron ore pellets is replaced by the export of HBI pellets from Year 2040. The export of HBI pellets is arbitrarily assumed to reach 6 Mtonnes in Year 2045. As the iron content of HBI pellets is higher than that of iron ore pellets, this corresponds to approximately 50% of LKAB's export of iron ore pellets in Year 2017.

Energy use. In Pathways 1, 2 and 3 (Figure 4, d–f), the replacement of the iron ore-based steel plant with an EAF results in reduced coal consumption in Year 2025. In Pathway 1 (Figure 4d), a further decline in the coal demand is observed in Year 2030, since the PCI into the blast furnace is replaced by biomass. Due to re-injection into the blast furnace of the top gas components CO and H_2 (as a reducing agent for the iron ore), the total consumption of coke for primary steel production in Pathway 1 is reduced by 27% compared to that in the conventional BF. In Year 2030, a 44% increase in natural gas consumption is observed relative to the current steel industry configuration, despite the reduction in natural gas consumption achieved through the using of biomass in the EAFs. In the TGRBF/CCS systems, natural gas is utilised for preheating the steam, as well as to meet the supplemental thermal energy demand of the CCS technology [23]. For Pathway 2 (Figure 4e), the demand for fossil fuel-based energy carriers, such as coke, coal, oil and natural gas, decreases by almost 100% in Year 2040, as compared to the demand linked to the current steel process configuration. This is attributed to the transition to the H-DR technology. However, in the period 2025–2040, the demand for fossil fuel-based energy carriers in Pathway 2 is higher compared to that in Pathway 1. Electricity use increases significantly, implying a need for electricity of around 12 TWh per year in Year 2045. For Pathway 3 (Figure 4f), the energy consumption level is similar to Pathway 2 until Year 2040 when the consumption of electricity increases dramatically, to reach 33 TWh per year in Year 2045.

Figure 5 shows the development of CO_2 emissions levels over time in the Swedish steel industry for the three pathways.

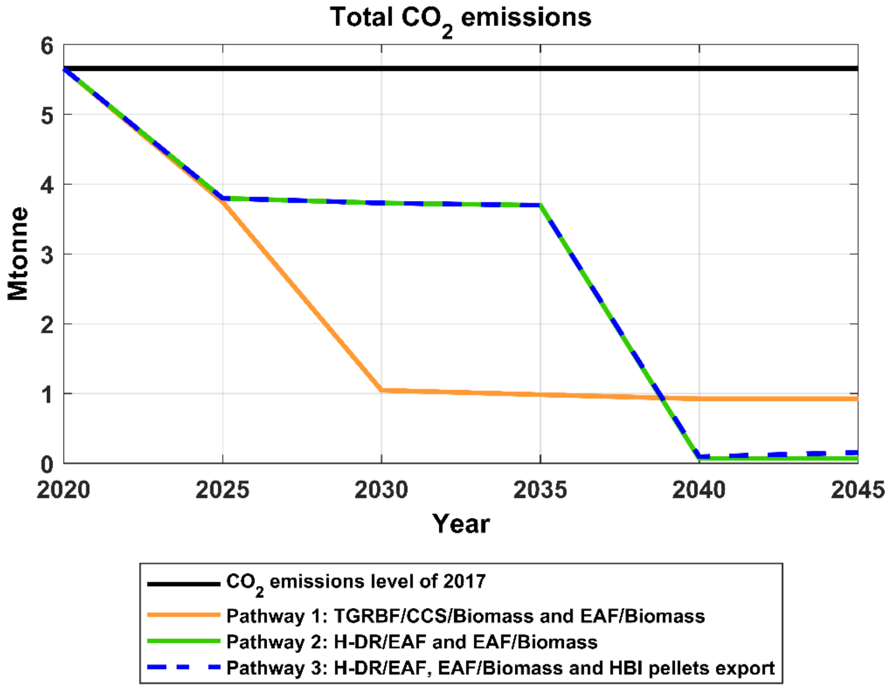

Figure 5. Development of CO_2 emissions levels for the Swedish steel industry pathways from Year 2020 to Year 2045. [*Source: Figure 7 in Paper I*]

The Pathways in relation to the CO_2 emission targets. As shown in Figure 5, already in Year 2030, Pathway 1 yields an 80% reduction in CO_2 emissions when applying CCS in combination with biomass substitution in the blast furnace, together with the replacement of an iron ore-based steel plant with an EAF. However, only an 83% reduction in CO_2 emissions from steel production can be obtained for Pathway 1. Pathways 2 and 3, which include electrification, enable further reductions in emissions compared to implementing CCS and the utilisation of biomass.

For all the investigated pathways, scrap metal consumption should increase from Year 2025 due to the replacement of BF/BOF with EAF. A global increase in scrap metal availability is expected due to steel stocks building up in emerging economies [35], while availability in the EU will stabilise, as the steel stock becomes saturated [36]. In this context, it should be important to prioritise innovation and technological developments related to delivering the highest quality of steel from recycling (EAF) (see for example [37]).

Since Sweden has an ongoing demonstration project on hydrogen-based steel production in the form of the HYBRIT project [6], Sweden is used as a case study to understand better the characteristics of the steel industry's transition to deep decarbonisation. Yet, decarbonisation of the steel industry will take different forms in different countries, depending on the local characteristics. The conditions for renewable electricity, the availability of biomass and CO_2 storage sites for CCS options, and ambitions regarding the energy transition will all significantly affect the feasibility of decarbonisation options. Thus, the timing and rate of emissions reductions vary depending on the prevailing conditions in each country.

4.2 Impacts of electricity price variations on the electrified steel production

The results from the case study in **Paper I** indicate that electrification of the steel industry via the H-DR process requires a significant amount of electricity. The results from **Paper I** also show that the cost of electricity is expected to be a substantial part of the cost of the H-DR steel-making process. In **Paper II**, we investigate how electricity price variations (see Figure 3) impact the investments in, and the operation of, steel production units (see Figure 1) in the H-DR steel-making process.

Figure 6 presents the distribution of the production cost per tonne of steel for the Year 2018 and Year 2050 price profiles for the wind-dominated electricity system of the northern UK and the solar-dominated electricity system of southern Germany. In the case of the Year 2050 price profiles, the modelling results are compared to the production costs with the assumption that the steel production capacities are operating continuously during all hours, i.e., without investments in storage (the *minimum investment level* case). The steel production cost is calculated as the sum of the annualised investment cost, raw material costs, DR shaft furnace start-up cost, electricity cost, and the other O&M costs, all of which are expressed per tonne of steel produced (i.e., as €/t). The cost of raw materials (ore, lime, alloys) constitutes a large share (up to 51%) of the production cost in all cases.

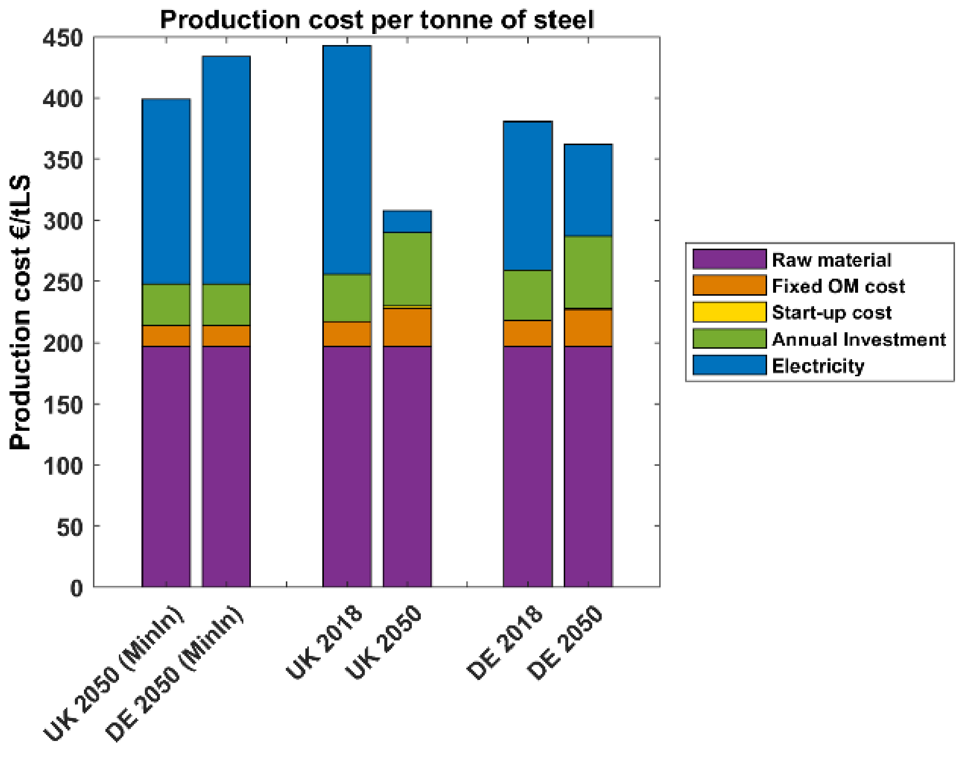

Figure 6. Production costs per tonne of steel of the steel-making process with the *minimum investment level* in steel production capacity (no storage and operation is at installed capacity all hours of the year) in northern UK and southern Germany in Year 2050 (MinIn), as well as for the modelled H-DR steel-making process for the two electricity price profiles in the northern UK and southern Germany for Year 2018 and Year 2050. tLS, tonne of liquid steel. [*Source: Figure 5 in Paper II*].

Figure 6 shows that the cost of electricity constitutes a large share of the production cost, with the exception of the UK in Year 2050, reflecting the strong availability of wind power generation and low production cost in this region. The results show that the cost of electricity can be reduced, with an increase in investment costs as a consequence. Investments in storage for the H-DR steel-making process, which allows for flexible electricity consumption, yield production cost reductions of 23% and 17% in northern UK and southern Germany, respectively, as compared to the *minimum investment level* cost. This is despite the fact that the annual investment costs increase almost two-fold compared to the *minimum investment level*. In the northern UK region, the cost of steel is lower in Year 2050 than in Year 2018, also in the case of continuous operation. This is due to a reduction in the average annual electricity price compared to Year 2018 (large share of wind power with low production cost). In contrast in southern Germany, the cost of steel is higher in Year 2050 than in Year 2018 unless the H-DR steel-making process is implemented for flexible electricity consumption.

4.3 Steel production and electricity system

In **Paper II**, the electricity price is applied exogenously in the model, which means that the response of the electricity system to the new demand for electricity from the steel industry is missing. There is a lack of understanding as to how an extensive deployment of the H-DR steel-making process would influence future investments in steel plants and electricity generation in different regions. Therefore, the mutual impacts of electrified steel production and the electricity system are investigated in **Paper III**.

4.3.1 Steel plant locational determinants

Based on the results from the modelling in **Paper III**, the main determinants of the cost-optimal localisation of the units in the electrified steel process were identified. Nine scenarios that differed with respect to the assumptions made regarding key parameters, such as: (i) the cost of using new sites for steel production; (ii) transport costs; (iii) commodities export; (iv) flexibility in the operation of the DR shaft furnace; and (v) the demand for steel, were investigated to analyse how the cost-optimal location of the electrified steel production capacity depends on these parameters. The scenarios are described in detailed in **Paper III**. Figure 7 shows the locational determinants for each scenario and commodity exports to regions with demands for steel.

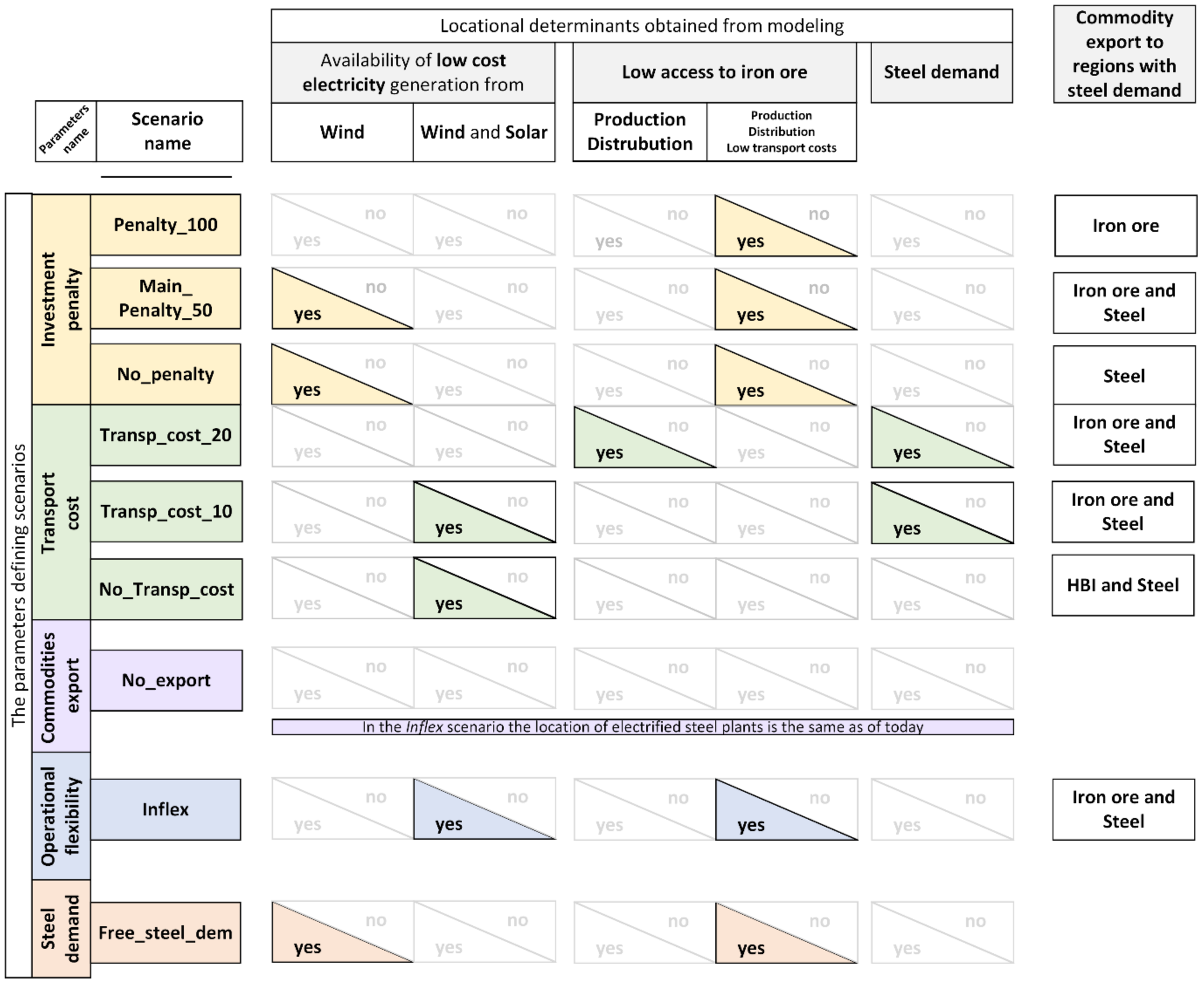

Figure 7. Summary of the parameters that define: the investigated scenarios and scenarios names; the locational determinants; and commodity exports to regions with steel demand. The colour of the scenario name correlates with the colour of the parameter varied in the scenario and the colour of the locational determinant that impacts the allocation of steel plants. [*Summary of what is investigated in Paper III*]

The modelling results from **Paper III** show that if the cost of establishing steel production capacity in regions that currently lack steel production capacity is high (Penalty _100), it is cost-efficient to locate steel production capacity in regions where there is low-cost access to iron ore. However, if the cost of establishing new sites for steel production is low (*Main_Penalty_50* and *No_penalty* scenarios), *the availability of low-cost electricity generation* determines the cost-efficient location of steel production. Furthermore, if the cost of establishing steel production capacity in regions that currently lack steel production capacity is high there is export of iron ore to regions with steel demand (i.e., regions that currently have primary steel production). In contrast, if the cost of establishing new sites for steel production is low, there is export of steel.

At a low cost of transporting commodities, as applied in the *Transp_10_cost* and *No_transp_cost* scenarios, *the availability of low-cost electricity generation* from wind and solar sources becomes a factor that defines the location of steel plants. If the transportation cost is not significantly high, HBI is traded between regions. Regions with good availability of low-cost electricity generation from wind power and an investment penalty imposed on steel production capacities import iron and export HBI and steel to regions that have a high steel demand and existing steel production.

In the *No_export* scenario, when exports of HBI and steel are not allowed, the locations of the electrified steel plants are the same as those today, since the steel demand of the investigated regions is given by the existing, annual ore-based steel production in this scenario. The *steel demand* and the *number of hours with low net load* define the levels of investments in steel production capacities and storage units in the *No_export* scenario, since there is no possibility to reduce the steel production cost through the allocation of steel production capacity to a region without existing steel production but with strong availability of low-cost electricity.

In the *Inflex* scenario, the DR shaft furnace has constant HBI production and the location determinants are *the existence of steel production* and *availability of low-cost electricity generation* from wind and solar sources. In the *Inflex* scenario, the inflexible operation of the DR shaft furnace is compensated for by large storage units. In the *Free_steel_dem* scenario, the total annual ore-based steel production of northern Europe represents a shared steel demand and the location determinants are *low transportation cost* and *availability of low-cost electricity generation* from wind and solar sources. The results obtained for the *Free_steel_dem* scenario also show that market proximity (i.e., under the assumption of regional steel demand) has a low impact on steel plant allocation.

In the modelling performed in **Paper III**, there are several important factors that are unknown. Steel is a globally traded commodity and steel demand on the international level is affected by several factors, e.g., the state of the global economy. As a consequence, the development of steel demand in the regions is difficult to predict. Changes in future demand and production levels will obviously have major impacts on the results. The capacities of the ports and storage times are neglected because we assume that the ports are always available to receive and store commodities. Capacity constraints, availability collection and distribution systems in a port, as well as specific safety during HBI transportation, are relevant issues to take into consideration when analysing access to port services. These issues warrant further investigation.

4.3.2 Electricity generation

Figure 8 shows the electricity generation (in TWh) for Year 2050 in the absence of electrified steel production (left-hand panel), and how this generation differs (in TWh) compared to the different scenarios (see Figure 3) with electrified steel production (right-hand panel) in a) England (UK1); and b) the Baltic regions (BAL).

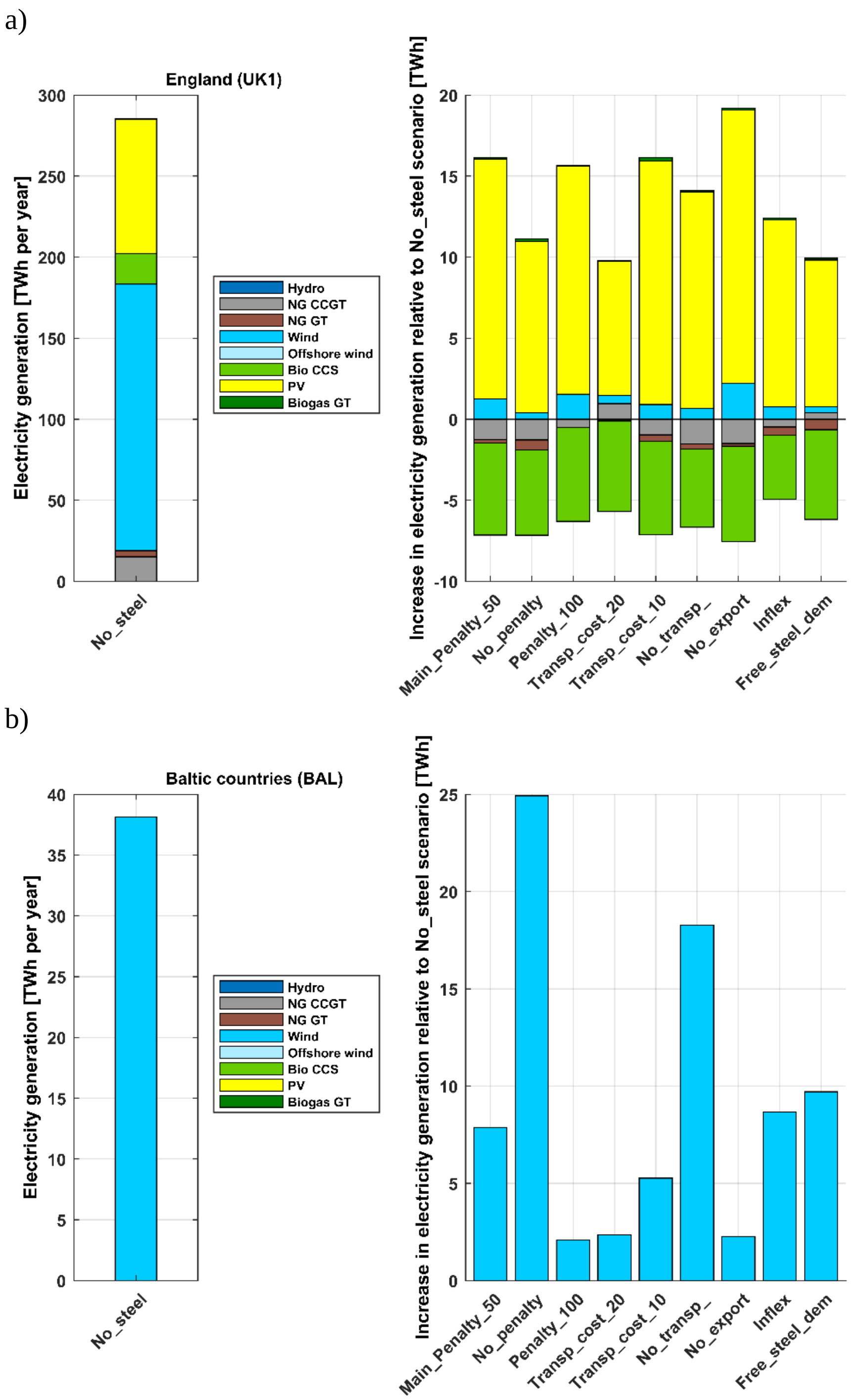

Figure 8. Total annual electricity generation (in TWh) in Year 2050 for the scenario without electrified steel production (left-hand panel) and the differences (in TWh) in electricity generation between an electricity system without electrified steel production and the scenarios with electrified steel production (right-hand panel) in a) England (UK1) and b) the Baltic regions (BAL). NG, natural gas; CCGT, combined cycle gas turbine; GT, gas turbine; CCS, carbon capture and storage. [*Source: Figure 11b and Figure A5b in Paper III*]

The modelling described in **Paper III** gives that wind power and solar power dominate the annual generation profile in Year 2050 in northern Europe. The varying renewable generation is complemented by flexible thermal generation based on natural gas and biogas. The CO_2 emissions from the combustion of natural gas are compensated for by capturing and storing the CO_2 emitted during biomass-based electricity generation. The additional electricity demand from the steel industry is mainly covered by increased production from wind and solar power, while at the same time it reduces production from natural gas-based generation technologies.

The additional electricity demand from electrified steel production in regions with high-to-medium steel demand [such as England (UK1)] promotes an increase in solar power generation and a decrease in fossil fuel-based generation (Figure 6a). Since the electrified steel production results in a decrease in electricity generation from natural gas-based electricity generation technologies, electricity generation from the bio-CCS technology, which provides negative emissions to compensate for the fossil-derived emissions, is also reduced.

The modelling gives that in the regions that have a wind power-dominated electricity mix in Year 2050, and consequently extended low-net-load hours, the additional electricity demand from steel production is met by increased wind power production. In these regions, the additional electricity demand is particularly high in the *No_penalty* and *No_transp_cost* scenarios, for which strong availability of low-cost electricity generation has a substantial impact on the location of steel production (Figure 8b).

5. Conclusions

The results obtained in the present work show that:

The achievement of close-to-zero emissions in the steel industry up to Year 2045 is not feasible without the implementation of breakthrough technologies, i.e., hydrogen, CCS and biomass. While new steel-making processes are critical, energy prices, technology costs, the availability of raw materials, and the regional policy landscape will all shape the steel industry's technology portfolio. Access to low-cost renewable electricity provides a competitive advantage for the hydrogen-based DRI route.

In the future electricity system, in which a large share of variable renewable electricity is expected, configuration of the steel-making process in terms of unit size and storage units so as to match the electricity system context is important. The results from the modelling show that steel production costs can be reduced by up to 20% if steel production follows electricity price variations. The extent to which the cost of electricity for steel production can be reduced depends on the operational flexibility of the steel production capacity and the extents of hydrogen and HBI storage. To achieve a low electricity cost for steel production, investments in overcapacity are required.

The modelling shows that the replacement of conventional primary steel production in northern Europe with steel production based on the H-DR technology can increase the electricity demand by 11% (by 183 TWh). The spatial allocation of the electrified steel production capacity could differ from the present day allocation of steel plants. It is found that the availability of low-cost electricity has a strong impact on the location of the steel production capacity at a low-to-moderate cost of using new sites for steel production, a low-to-moderate cost for trading commodities and inflexible operation of the DR shaft furnace.. It is shown that the electricity demand from the steel industry in all the regions investigated are, when assuming zero CO_2 emissions in Year 2050, met primarily by an increased generation of variable renewable electricity (i.e., wind and solar power).

6. Future work

Possible future directions for the work presented in this thesis are suggested below.

The steel industry is a complex industry that is intrinsically linked to the global economy. Different countries play different roles in the steel industry chain, forming a complex global trade network. **Paper III** includes only the steel industry of northern Europe. A study that analyses electrification of the steel industry on the global level would be of interest. Based on the modelling results from **Paper III**, we hypothesise that the preferable locations of electrified steel production would be regions with large-scale iron ore mining and excellent availability of low-cost electricity. A study of electrification of the global steel industry would highlight potential changes in global commodity trade flows and the geographical allocations of the electricity demand and investments that are needed to meet these challenges.

Deep cuts in CO_2 emissions from the steel industry are achievable by applying CCS together with biomass and steel production process electrification (i.e., H-DR steel-making) (**Paper I**). Bio-CCS implementation offers opportunities for negative emission across the European iron and steel industry [38]. Thus, a modelling study that analyses a combination of the different ways to reduce CO_2 emissions from steel production would be of interest. Such a study could increase understanding of the regional distribution of mitigation technologies across the steel sector and could examine the competition between the electricity system and the steel industry for resources such as electricity and biomass.

It is more challenging to decarbonise energy-intensive industries (such as steel, metallurgy, cement, paper and chemicals) than other sectors due to their heterogeneity, CO_2 intensities, trade and cost sensitivities, and long facility lifetimes. The rapid decline in the cost of renewable electricity and the growing potential for emissions reduction in energy-intensive industries through switching from fossil fuel-based energy demands and feedstocks towards electricity [39], [40] make electrification an attractive option. It would be worthwhile to investigate the combined effects of electrified energy-intensive industries on the electricity system. Such a study could provide information on competition (i.e., for low-cost electricity and grid capacity) and synergies (i.e., the sharing of infrastructure) between industries.

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